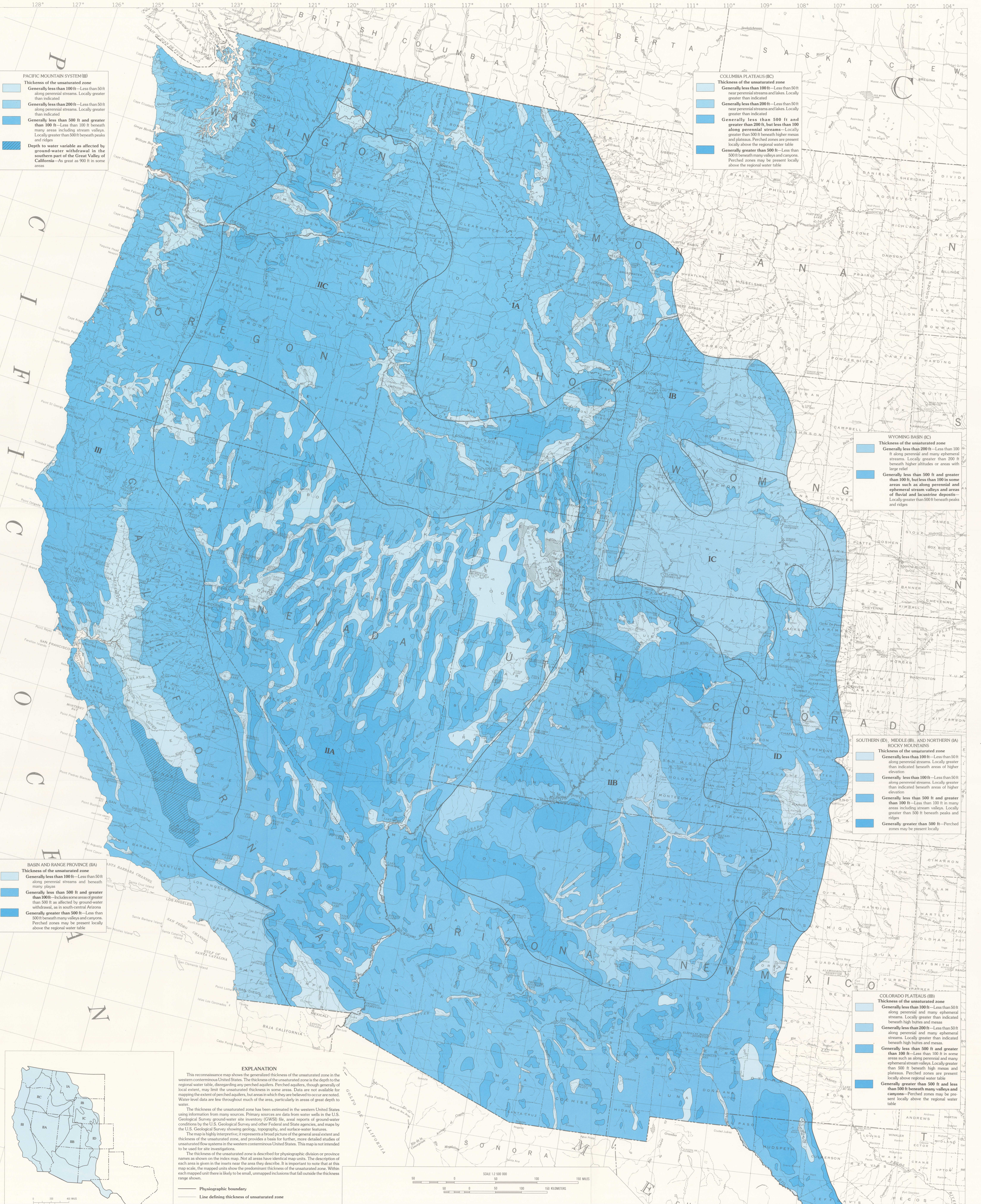
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

HYDROLOGIC INVESTIGATIONS
ATLAS HA-715



PACIFIC MOUNTAIN SYSTEM (III)

**Thickenss of the unsaturated zone**

- ▢ **Generally less than 100 ft**—Less than 50 ft along perennial streams. Locally greater than indicated
- ▢ **Generally less than 200 ft**—Less than 50 ft along perennial streams. Locally greater than indicated
- ▢ **Generally less than 500 ft and greater than 100 ft**—Less than 100 ft beneath many areas including stream valleys. Locally greater than 500 ft beneath peaks and ridges
- ▨ **Depth to water variable as affected by ground-water withdrawal in the southern part of the Great Valley of California**—As great as 900 ft in some areas

COLUMBIA PLATEAUS (IIC)

**Thickness of the unsaturated zone**

- ▢ **Generally less than 100 ft**—Less than 50 ft near perennial streams and lakes. Locally greater than indicated
- ▢ **Generally less than 200 ft**—Less than 50 ft near perennial streams and lakes. Locally greater than indicated
- ▢ **Generally less than 500 ft and greater than 200 ft, but less than 100 along perennial streams**—Locally greater than 500 ft beneath higher mesas and plateaus. Perched zones are present locally above the regional water table
- ▢ **Generally greater than 500 ft**—Less than 500 ft beneath many valleys and canyons. Perched zones may be present locally above the regional water table

WYOMING BASIN (IC)

**Thickness of the unsaturated zone**

- ▢ **Generally less than 200 ft**—Less than 100 ft along perennial and many ephemeral streams. Locally greater than 200 ft beneath higher altitudes or areas with large relief
- ▢ **Generally less than 500 ft and greater than 100 ft, but less than 100 in some areas such as along perennial and ephemeral stream valleys and areas of fluvial and lacustrine depostis**—Locally greater than 500 ft beneath peaks and ridges

SOUTHERN (ID), MIDDLE (IB), AND NORTHERN (IA) ROCKY MOUNTAINS

**Thickness of the unsaturated zone**

- ▢ **Generally less than 100 ft**—Less than 50 ft along perennial streams. Locally greater than indicated beneath areas of higher elevation
- ▢ **Generally less than 100 ft**—Less than 50 ft along perennial streams. Locally greater than indicated beneath areas of higher elevation
- ▢ **Generally less than 500 ft and greater than 100 ft**—Less than 100 ft in many areas including stream valleys. Locally greater than 500 ft beneath peaks and ridges
- ▢ **Generally greater than 500 ft**—Perched zones may be present locally

BASIN AND RANGE PROVINCE (IIA)

**Thickness of the unsaturated zone**

- ▢ **Generally less than 100 ft**—Less than 50 ft along perennial streams and beneath many playas
- ▢ **Generally less than 500 ft and greater than 100 ft**—Includes some areas of greater than 500 ft as affected by ground-water withdrawal, as in south-central Arizona
- ▢ **Generally greater than 500 ft**—Less than 500 ft beneath many valleys and canyons. Perched zones may be present locally above the regional water table

COLORADO PLATEAUS (IIB)

**Thickness of the unsaturated zone**

- ▢ **Generally less than 100 ft**—Less than 50 ft along perennial and many ephemeral streams. Locally greater than indicated beneath high buttes and mesas
- ▢ **Generally less than 200 ft**—Less than 50 ft along perennial and many ephemeral streams. Locally greater than indicated beneath high buttes and mesas.
- ▢ **Generally less than 500 ft and greater than 100 ft**—Less than 100 ft in some areas such as along perennial and many ephemeral stream valleys. Locally greater than 500 ft beneath high mesas and plateaus. Perched zones are present locally above regional water table
- ▢ **Generally greater than 500 ft and less than 500 ft beneath many valleys and canyons**—Perched zones may be present locally above the regional water table

## EXPLANATION

This reconnaissance map shows the generalized thickness of the unsaturated zone in the western conterminous United States. The thickness of the unsaturated zone is the depth to the regional water table, disregarding any perched aquifers. Perched aquifers, though generally of local extent, may limit the unsaturated thickness in some areas. Data are not available for mapping the extent of perched aquifers, but areas in which they are believed to occur are noted. Water-level data are few throughout much of the area, particularly in areas of great depth to water.

The thickness of the unsaturated zone has been estimated in the western United States using information from many sources. Primary sources are data from water wells in the U.S. Geological Survey ground-water site inventory (GWSI) file, areal reports of ground-water conditions by the U.S. Geological Survey and other Federal and State agencies, and maps by the U.S. Geological Survey showing geology, topography, and surface-water features.

The map is highly interpretive; it represents a broad picture of the general areal extent and thickness of the unsaturated zone, and provides a basis for further, more detailed studies of unsaturated flow systems in the western conterminous United States. This map is not intended to be used for site investigations.

The thickness of the unsaturated zone is described for physiographic division or province names as shown on the index map. Not all areas have identical map units. The description of each area is given in the insets near the area they describe. It is important to note that at this map scale, the mapped units show the predominant thickness of the unsaturated zone. Within each mapped unit there is likely to be small, unmapped inclusions that fall outside the thickness range shown.

**Physiographic boundary**

**Line defining thickness of unsaturated zone**

SCALE 1:2 500 000

- I Rocky Mountain System
  - A Northern Rocky Mountains
  - B Middle Rocky Mountains
  - C Wyoming Basin
  - D Southern Rocky Mountains
- II Intermontane Plateaus
  - A Basin and Range province
  - B Colorado Plateaus
  - C Columbia Plateaus
- III Pacific Mountain System

Index map showing physiographic divisions and provinces (modified from Fenneman, 1946).

# RECONNAISSANCE STUDY OF THE THICKNESS OF THE UNSATURATED ZONE IN THE WESTERN CONTERMINOUS UNITED STATES

By

M.S. Bedinger and William H. Langer

1989

## INTRODUCTION

In 1984, the U.S. Geological Survey began a study of the geologic and hydrologic characteristics of the unsaturated zone in the western conterminous United States. The study area extends from the eastern edge of the Rocky Mountains westward and includes all or parts of the 12 westernmost conterminous States. The goal of the study is to characterize unsaturated flow systems to aid in identifying environments in the western United States that may merit further study for isolation of hazardous waste, including high- and low-level radioactive waste and other toxic waste.

The major physiographic areas discussed in this report (see index map below thickness map) are: (1) Rocky Mountain System consisting of the Southern, Middle, and Northern Rocky Mountains, and the Wyoming Basin; (2) Intermontane Plateaus consisting of the Basin and Range province, and the Colorado and Columbia Plateaus; and (3) Pacific Mountain System (Fenneman, 1946). Two of these areas, the Colorado and Columbia plateaus, exhibit a variety of geohydrologic conditions, and therefore are further subdivided in the discussions that follow.

Outstanding features peculiar to the mountainous area of the Rocky Mountain and the Pacific Mountain Systems are the high rugged mountains and steep relief. These mountains receive greater precipitation than do the lower parts of the otherwise dry western United States. Generally moisture-laden air masses move eastward across the continent, and the mountains force them to higher, cooler altitudes. As the air cools, moisture condenses and precipitates. As a result, the Rocky Mountain and Pacific Mountain Systems have annual precipitation in excess of 30 in.

The Wyoming Basin of the Rocky Mountain System and the Basin and Range province, Colorado Plateaus, and Columbia Plateaus of the Intermontane Plateaus generally have lower altitudes and less relief than do the mountainous areas. The climate throughout most of these provinces generally is semiarid to arid. Annual precipitation is generally less than 16 in. throughout most of the area, and is less than 4 in. in some parts. The mean annual free-water-surface evaporation ranges from 20 to 100 in. A large part of the study area is subject to a water deficit because potential evapotranspiration exceeds precipitation. As a consequence of the large water deficit, ground-water recharge generally is small, surface runoff is small, perennial streams and lakes are few, and the depth to ground water commonly is large. The generalized thickness of the unsaturated zone (the depth to ground water), in the western conterminous United States is presented on the map.

## ROCKY MOUNTAIN SYSTEM

### SOUTHERN, MIDDLE, AND NORTHERN ROCKY MOUNTAINS

The Southern Rocky Mountains consist of two south-trending series of ranges extending from southern Wyoming to northern New Mexico. The two series of ranges are separated in places by broad basins and river valleys. The mountains consist of a series of anticlinal uplifts; uplifting began at the end of the Cretaceous Period and continued into the Tertiary Period. Precambrian rocks crop out throughout the central area of most of the anticlinal mountain ranges. Two large granitic batholiths are exposed among the Precambrian rocks, one in south-central Colorado and the other in southern Wyoming. During the Cenozoic Era, igneous rocks were intruded in the province and extensive lava eruptions occurred in the western part of the province. The Southern Rocky Mountains province contains the highest peaks in the system, many are higher than 14,000 ft. Passes through the mountains usually are higher than 9,000 ft.

The Middle Rocky Mountains includes anticlinal folding of Paleozoic and Mesozoic rocks exposing Precambrian cores and uplifted, block-faulted Paleozoic strata intruded by stocks. The mountain ranges are separated by basins underlain by Paleozoic, Mesozoic, and Tertiary sedimentary rocks. The Yellowstone area in northwestern Wyoming is a high plateau underlain by as much as 10,000 ft of volcanic rock of late Tertiary and Quaternary age.

The Northern Rocky Mountains consist of mountains developed from block-faulted and thrust-faulted Paleozoic formations and anticlinal folding of rocks. Granitic batholith plateaus and highlands occur in Montana, Idaho, and Washington. Mountain ranges are separated by linear north- to northwest- trending valleys narrower than the broad basins that separate mountain ranges in the Southern Rocky Mountains. A rift valley extends into the province from Canada.

The depth to water in the Southern, Middle, and Northern Rocky Mountains is controlled largely by the available water for recharge, the generally mininal permeability of the rocks, and the large relief of the mountains. Precipitation at higher altitudes generally is 30 in. or more per year and abundant water is available from rainfall and snowmelt for direct runoff and infiltration. Many streams and lakes at high altitudes in these provinces are perennial from above timberline to the lower hill slopes. The greatest depths to water are inferred to occur beneath the highest peaks and ridges. True perched water tables probably are not extensively developed in crystalline igneous and metamorphic rocks or in steeply inclined sedimentary rocks. However, the permeability distribution of the crystalline rocks is variable and depths to water and quantities of water encountered in wells may differ greatly within short distances.

In plateau areas underlain by gently dipping sedimentary or volcanic rocks, perched water tables may be significant. Broad, low intermontane areas, receive less precipitation than the adjacent mountains. In intermontane basins underlain by gently dipping sedimentary rocks, and in large valleys, depths to water are generally less than 100 ft. In the Southern Rocky Mountains along the eastern flank, and in areas of relatively shallow incision of streams and rounded hills, depths to water predominantly are less than 100 ft below land surface.

### WYOMING BASIN

The Wyoming Basin is a broad structural depression bordered on the north, west and southwest by the Middle Rocky Mountains and on the south by the Southern Rocky Mountains. The basin is underlain by Paleozoic, Mesozoic, and Tertiary strata. It is at an altitude between 7,000 and 8,000 ft and has relatively low relief. Annual precipitation ranges from about 8 to 12 in. per year; surface drainage in part of the basin is internal. The thickness of the unsaturated zone generally is less than 200 ft.

## INTERMONTANE PLATEAUS

### BASIN AND RANGE PROVINCE

The Basin and Range province, as its name implies, consists of low-lying desert basins interrupted by mountain ranges that tend to form parallel north-trending ridges. Altitudes of the basins range from below sea level to greater than 6,000 ft above sea level. The summits of most ranges are less than 10,000 ft above sea level. The basins typically are wider than the ranges.

The Basin and Range province is characterized by complex structure and stratigraphy. Tertiary and Quaternary tectonic events that created the characteristic northward-trending mountain blocks and basins were accompanied by volcanism and plutonism. These geologically young events were a continuation of a long geologic history of tectonic episodes. Although sections of the Basin and Range province share a catastrophic history of earth movement and igneous activity, various sections have distinctly different ages, terrain, rocks, and structure.

Bedrock includes Precambrian metamorphic rocks; Paleozoic through Quaternary intrusive and volcanic rocks; and Paleozoic, Mesozoic, and lower Tertiary sedimentary rocks. Bedrock permeability, which generally is less than the permeability of basin-fill deposits, generally retards ground-water flow between basins (fig. 1). However, where bedrock permeability has been increased because of jointing, fracturing, and solution of carbonate rocks, ground-water flow between basins may be significant.

Basin-fill deposits began to accumulate concurrently with the origin of the basin-and-range structure in the middle Tertiary and has continued in the Holocene. The composition of basin fill ranges from clay and silt to sand and gravel. Playas, which occupy low areas in some basins, contain evaporite deposits that include carbonate rocks and simple to complex salts. Permeability of basin fill depends on grain-size distribution and the degree of consolidation and cementation. In some basins, deeper basin-fill deposits are more consolidated and less permeable than the overlying, less consolidated deposits. The basin-fill deposits commonly are coarse grained near the perimeters of the basins and fine grained in the central parts of the basins.

Climate in the Basin and Range province is arid to semiarid; annual precipitation averages about 11 in. Variability in areal distribution of precipitation is directly related to topographic relief between the ranges and the intervening basins. Precipitation varies from less than 4 in. in the basins, to more than 20 in. at higher altitudes in many of the ranges. The mean annual free-water surface evaporation ranges from 35 to 100 in.

Average annual runoff from the Basin and Range province generally is less than 0.2 in. (Busby, 1966). The few perennial streams that originate within the Basin and Range province have their sources at higher altitudes in the ranges within the province, or the bounding highlands and ranges, principally of the Pacific Mountain System or the Colorado Plateaus. The two largest perennial streams flowing through the province, the Colorado River and the Rio Grande, originate outside the province.

Areas of unsaturated zones greater than 500 ft thick occur in three general situations in the Basin and Range. The first situation is where basin fill or densely fractured volcanic rock is thick and the underlying bedrock is permeable carbonate rocks. This situation accounts for the largest contiguous areas of thick unsaturated zones in southern Nevada.

Elsewhere, most of the areas of thick, unsaturated zones occur under high mountain ranges. This second situation is evidenced by the lack of perennial streams or springs in the mountain ranges, by deep water levels in wells, and by the depth of dry mine shafts in the mountain ranges.

The third situation where thick, unsaturated zones occur is in areas of little recharge coinciding with areas of deeply incised streams draining permeable basin fill. These are narrow areas that do not show at this map scale.

### COLORADO PLATEAUS

The Colorado Plateaus have a varied landscape of high plateaus with deeply incised canyons, mountains, deserts, and badlands. The description of the physiography, structure, and rocks of the Colorado Plateaus can be separated into the Grand Canyon, Navajo, Datil, Uinta Basin, High Plateaus and Canyon Lands, sections (fig. 2). On a large scale, the province is a plateau underlain by flat to gently dipping sedimentary rocks. The province contains some small mountain ranges and extinct volcanoes and lava fields, and has been modified by erosion. The plateau surface is greater than 5,000 ft, with some plateaus and peaks reaching over 11,000 ft.

The rocks that underlie the province are principally Paleozoic to Cenozoic sandstone, shale, and limestone. Unconsolidated deposits are relatively minor. Great differences occur in the permeabilities of the bedrock. The sandstone and limestone are the principal sources of ground water and are recharged where they crop out in the highlands. The shale confines water in the aquifers down dip from the recharge areas (fig. 3).

The climate in the Colorado Plateaus is arid to semiarid. Variability in areal distribution of precipitation is directly related to topographic relief. In much of the interior, the average annual precipitation is less than 10 in., whereas along the bordering high mountain ranges, precipitation exceeds 20 in. The mean annual free-water-surface evaporation ranges from 40 to 80 in.

As in the Basin and Range province, the large quantity of water lost by evaporation and transpiration compared with that received from precipitation results in little recharge to ground water, little annual runoff, and few perennial lakes and streams. A few streams issuing from the mountains are perennial for short distances into the valleys, but rarely extend far from the mountain front. A few large streams and springs in deep canyons locally drain the ground-water system, which results in thick unsaturated zones beneath the adjacent uplands. The draining by incised rivers is complicated by confining beds that retard downward movement of water and locally result in springs high on the canyon walls, and by the occurrence of faults that locally interrupt the continuity of confining beds.

### Grand Canyon Section

The Grand Canyon section includes Precambrian rocks overlain by about 4,000 ft of Paleozoic formations. The Grand Canyon incised by the Colorado River exposes the entire sequence of Paleozoic formations and extends into the Precambrian rocks, reaching a maximum depth of more than 5,000 ft. The Paleozoic rocks dip slightly because of broad warping and a few major steep-angle faults. Tertiary and Quaternary lava flows unconformably overlie the Paleozoic formations in the southeastern part of the section in, and north, of the Grand Canyon.

The stratigraphic controls on ground-water movement and spring horizons in the Grand Canyon are illustrated in figure 4. Large springs that issue from high up on the north side of the canyon wall issue from the Muav Limestone of Cambrian age, which overlies the thick, less-permeable Bright Angel Shale of Cambrian age. Huntoon (1974 and 1977) has determined that the springs are controlled by broad flexures which control the dips of the formations, and by faults and joints. The layering sequence of the aquifers and confining beds in conjunction with the faults and joints control the permeability of the flow system.

The depth to water in the Grand Canyon section is controlled by the deep canyons of the Colorado and Little Colorado Rivers and their major tributaries, the interbedded confining layers and water-bearing units, the presence of permeable, near-vertical, tension faults and minimal recharge. Although the Colorado River has incised the plateau more than 5,000 ft below the canyon rims, ground-water depths generally are less than 1,000 ft because of the presence of confining beds that retard downward movement of water. Locally, along generally north-trending alignments, normal faults disrupt the continuity of the confining beds. The top of the Hermit Shale of Permian age is at the base of a spring horizon in some areas, but is above the major springs that issue along the flank of the Kaibab Plateau at the base of the Muav Limestone. Faults are inferred to disrupt the continuity of the Hermit Shale. The confining beds and permeable fault zone in the Grand Canyon section cause considerable variability in the thickness of the unsaturated zone, which ranges from less than 100 ft to greater than 500 ft.

In the area south of the Colorado and Little Colorado Rivers, a large number of wells have water-level depths greater than 500 ft: some water-level depths are as great as 1,000 ft. In some wells, water levels are less than 100 ft below the land surface, possibly representing perched aquifers. Depths to water in the volcanic rocks in the southwestern part of the Grand Canyon section generally are less than 500 ft. The depth to water in the Grand Canyon is mapped as less than 500 ft. Here there is virtually no data from wells; major spring horizons occur at the base of the Redwall Limestone (Mississippian), in the Supai Formation (Pennsylvanian and Permian), and at the base of the Coconino Sandstone (Permian). Springs also issue from the Hermit Shale, Toroweap Formation, and Kaibab Limestone all of Permian age. Springs occur at depths of as much as 2,000 to 4,000 ft below the canyon rim. Some of the higher spring horizons may discharge from perched aquifers. North of the canyon, water levels beneath the plateau surfaces commonly are less than 200 ft, and in some areas are less than 100 ft beneath the plateau surface. Here, water levels are predominantly in formations above the Hermit Shale.

### The Navajo Section

The Navajo section is a structural depression consisting of two basins, the San Juan Basin, centered in northwest New Mexico, and a shallower basin centered beneath Black Mesa in northeast Arizona. The basins are separated by the Defiance upwarp. Paleozoic rocks form the rims of the basins, but in the basins the Paleozoic rocks are overlain by as much as 5,000 ft of Mesozoic rocks. In the San Juan Basin, the Mesozoic rocks are overlain by another 5,000 ft of Tertiary Age deposits. The thickness of the unsaturated zone is related to permeability of the predominantly slightly-dipping sedimentary rock sequence, local relief, and surface drainage. For most of the section the thickness of the unsaturated zone is less than 500 ft. However, the thickness of the unsaturated zone is greater than 500 ft beneath high mesas and buttes such as Black Mesa and the Defiance upwarp, and is less than 200 ft to less than 100 ft beneath valleys of perennial streams and of many ephemeral streams.

### The Datil Section

The Datil section of northeastern Arizona and northwestern New Mexico is a region of extensive thick lava flows of Tertiary and Quaternary age. A structural upwarp and a central-type volcano with numerous smaller volcanic centers and necks are in the northern part of the section. The extensive lava flows that extend south into the adjacent Basin and Range province locally have been deeply eroded. The thickness of the unsaturated zone ranges from greater than 500 ft beneath a few of the higher buttes and mesas to broad extensive areas of less than 200 ft.

### Uinta Basin

The Uinta Basin is a structural basin in northeastern Utah and northwestern Colorado. Beds of Paleozoic, Mesozoic, and Cenozoic age dip steeply to the south on the northern flank of the Uinta Basin. The resistant, gently dipping strata on the southern flank of the basin form the prominent south-facing Roan and Book Cliffs escarpments. Depths to ground water are less than 500 ft except in the mountains bordering the Roan and Book Cliffs where depths to water may exceed 500 ft. Here, perched aquifers may be present in the gently dipping sedimentary layers.

### High Plateaus of Utah

The High Plateaus of Utah at the western edge of the Colorado Plateaus consists of northerly trending fault blocks. The plateaus, 9,000 to 11,000 ft in altitude, some capped by lava, are underlain by Mesozoic and Tertiary formations. The thickness of the unsaturated zone probably is less than 500 ft in the high plateaus bordering the Basin and Range province, where precipitation is as great as 32 in. per year.

### Canyon Lands

The Canyon Lands area is in southwestern Colorado and southeastern Utah. The area consits of four large structural upwarps and intervening structural basins. As the name implies, canyons are the dominant feature. The thickness of the unsaturated zone in the Canyon Lands is affected greatly by: the generally arid climate; the layering of relatively impermeable gently dipping sedimentary beds; local topography; and the deeply incised stream channels. Perennial streams are the base level for discharge from the regional water-table flow system. For example, in Utah where the deeply incised streams have exposed the sandstone aquifers, depths to water beneath the adjacent high plateaus are nearly as deep as the canyons. Locally, as in southwestern Colorado, the gently dipping bedding sequence includes less-permeable layers resulting in numerous small springs from perched zones above the regional water table.

### COLUMBIA PLATEAUS

The Columbia Plateaus generally is a broad plateau area bordered on the north, east, and west by mountains (fig. 5). On the south the province grades into the Basin and Range province. The physiography, structure, and rocks of the Columbia Plateaus can be separated into the Walla Walla Plateau, the Snake River Plain, the Payette section, the Blue Mountain section, and the Harney section. Altitudes of the Columbia Plateaus commonly are between 1,600 and 6,000 ft, although the altitude in the Blue Mountain section locally exceeds 10,000 ft. Most of the Snake River Plain is exceptionally flat, interrupted only by the canyons of the Snake River and its tributaries, and by a few large buttes. In contrast, the Walla Walla Plateau has more relief in the form of anticlinal ridges, dissected canyons, dry falls, and scablands eroded by Pleistocene floods.

Climate in the Columbia Plateaus generally is arid to semiarid. The mountains bordering the province have a pronounced effect on the quantity and distribution of precipitation in the province. Annual precipitation at high altitudes surrounding the province exceeds 50 in., and exceeds 20 in. in the Blue Mountain section. Annual precipitation throughout most of the province is less than 20 in., generally ranging from 6 to 10 in. In areas of little precipitation, much of the water is likely to evaporate or run off soon after it falls, or if it infiltrates, it is likely to be transpired by vegetation. Potential evaporation exceeds average annual precipitation in most of the plateau lowlands. In these areas, precipitation probably only recharges the ground-water system during exceptionally wet periods, or during spring snowmelt when evapotranspiration is small. Recharge incidental to irrigation (infiltration during irrigation and seepage from canals) is the largest source of recharge at many places.

The outstanding feature typifying the hydrogeology of the Columbia Plateaus is the extensive occurrence of a thick sequence of lava flows. Most of the Snake River Plain in Idaho, as well as much of the area in southeastern Oregon and northern Nevada is underlain by Quaternary lava. In Washington and northern Oregon the flows are older, most dating back to the Miocene Epoch.

### Walla Walla Plateau

The Walla Walla Plateau occupies a structural depression that was downwarped during the Miocene and Pliocene while lavas were being erupted and sediments deposited. Lavas filled the central part of the basin while sediments deposited in lakes formed within and at the margins of the basin. The sequence of lava flows has a general thickness of 4,000 to 5,000 ft in the central part of the section, and tapers out on the prebasalt surface at the margins (Newcomb, 1972). Thicknesses of individual lava flows are variable, ranging from 10 to 200 ft; average thickness is about 100 ft, (Newcomb, 1972). Many of the basalt flows are extensive, having flowed considerable distances from fissures.

Late in the eruptive process, and perhaps during the period between successive lava flows, sediment was deposited and/or soil formed on the land surface. These sediments eventually were buried by subsequent flows. The interflow sediments occur throughout the Columbia Plateaus and may be aquifers or barriers to ground-water movement depending on their grain-size distribution.

The volcanic rocks of the Walla Walla Plateau transmit water primarily through permeable zones that occur at or near the contacts between some flow layers (fig. 6). Mineral alteration products and secondary mineralization in older basalts may decrease the size of the openings between flows or in joints, which in turn decreases the permeability of rocks. Areas of abnormally high permeabilities may be found where brecciated basalt or lava tubes occur.

Compared to horizontal flow rates, vertical movement between flows is relatively slow, since vertical movement is nearly perpendicular to the lava flows. Vertical movement is further impeded where fine-grained sediments are intercalated with the basaltic rocks. The Walla Walla Plateau basalts (Luzier and Burt, 1974) can be divided vertically into aquifers separated by shallow dipping confining zones, with each aquifer having its own identifiable potentiometric surface. Apparently there is only a very small component of flow across confining beds.

The areas of thickest unsaturated zones (greater than 500 ft) are beneath high plateaus near the Snake and Columbia Rivers. Although not mapped, local perched aquifers may overlie the regional ground-water system.

### Snake River Plain

The Snake River Plain is a structural downwarp filled mostly with Quaternary age lava flows. Sediments are intercalated with the lava flows, particularly near the basin margins. The total thickness of the lavas is unknown, but is estimated to be as much as 5,000 ft (Whitehead and Lindholm, 1985). Thicknesses of individual lava flows are variable, averaging 20 to 25 ft (Mundorff and others, 1964); the areal extent of individual flows commonly is tens to hundreds of square miles (Nace and others, 1975).

In the Snake River Plain, the Quaternary basalts commonly are unweathered, have abundant joints, and have broken or rubbly contact zones. These features result in permeable zones, even though intact matrix rock may have a negligible permeability. Zones of abnormally high permeability are located where brecciated zones or lava tubes or caves occur. As in the Walla Walla Plateau, vertical water movement between interflow zones is relatively slow, compared to horizontal flow rates. Vertical water movement is especially impeded where fine-grained sediments are intercalated with the basaltic rocks. These sediments occur primarily near basin boundaries, (particularly near the southeastern area) as discontinuous beds a few feet to tens of feet thick (Whitehead and Lindholm, 1985). Even though permeability in the vertical direction is small compared with the horizontal component, significant water movement can occur in the vertical direction because of the large hydraulic gradient and cross-sectional area, particularly through the unsaturated zone.

Extensive areas of the eastern part of the Snake River Plain, including most of the northwest and central plain area, have unsaturated zones greater than 500 ft thick. With a few local exceptions, the only places where the water table comes within 100 ft of the land surface is in the northern part of the plain, and in a band along the Snake River.

Throughout the Snake River Plain, the occurrence of thick unsaturated zones generally results from minimal recharge in areas underlain by rock of high hydraulic conductivity, in particular Basalt of the Snake River Group. The lack of altered zones and secondary mineralization of the basalts, and the rather limited areal extent of individual flows has resulted in a relatively large vertical conductivity. This contributes to the great thickness of the unsaturated zone in large areas of the Snake River Plain.

### Payette Section

The geology of the Payette section is dominated by a series of Tertiary and Quaternary sedimentary rocks and basalt flows that have a combined thickness of as much as 10,000 ft (Lindholm, 1981). Throughout the Payette section, the thickness of the unsaturated zone is less than 500 ft. The thickness of the unsaturated zone exceeds 500 ft in only a few relatively small, isolated localities.

### Blue Mountain Section

The Blue Mountain section is formed by an uplift of Paleozoic and Mesozoic sedimentary rocks and intrusive Cenozoic rocks. The structure and topography of this section have more in common with the Northern Rocky Mountains than they do with the rest of the Columbia Plateaus. Many streams and lakes in this section are perennial surface expressions of the water table. In general, the thickness of the unsaturated zone is less than 500 ft, with a few areas being less than 100 ft.

### Harney Section

The Harney section is a volcanic plain at the southwest corner of the Columbia Plateaus. The plain is underlain by nearly horizontal, Quaternary lava flows, and has little local relief except at volcanic centers. There is no exterior drainage except at the edges of the section. In general, the thickness of the unsaturated zone is less than 500 ft.

## PACIFIC MOUNTAIN SYSTEM

The Pacific Mountain System borders the Pacific Ocean and consists of mountain ranges and intervening valleys (fig. 7). The mountains are responsible for the deserts to the east because they intercept incoming moisture from the Pacific air masses and consequently receive the greatest quantities of precipitation in the western United States. Annual precipitation in the mountains decreases from north to south. Precipitation decreases from 150 in. in the Olympic Mountains of Washington, to 90 to 112 in. in the Cascade Range of Oregon and Washington, to 40 to 80 in. in the Sierra Nevada of California, to 30 to 40 in. in the Transverse Ranges of southern California.

Because of the substantial precipitation, the thickness of the unsaturated zone commonly is less than 500 ft. A large area in California where the depth to water is affected by withdrawals is shown by a ruled pattern. Well data are meager in the mountain ranges; surface-water features indicate the depth to water is much less than 500 ft throughout a large part of the Sierra Nevada Mountains, Cascade Range, and Olympic Mountains.

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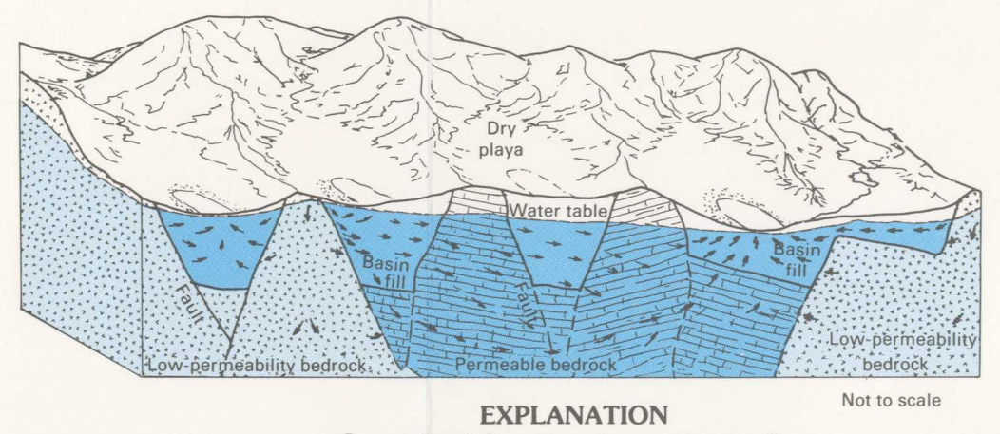

Figure 1.—Generalized physiography, and ground-water flow in the Basin and Range province (modified from Eakin and others, 1976).

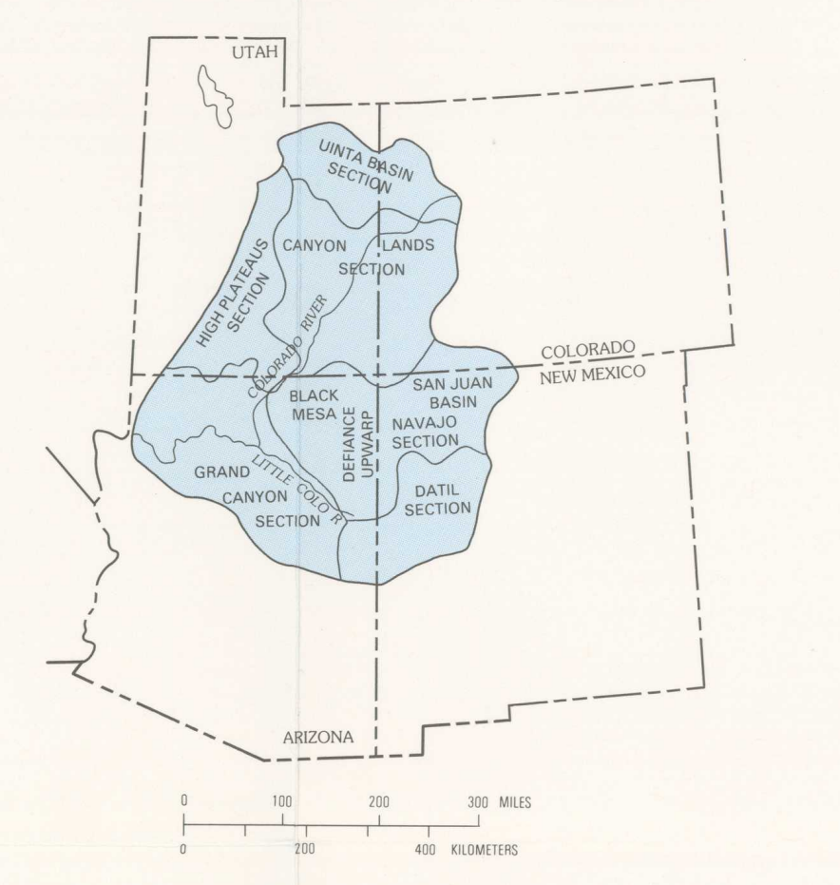

Figure 2.—Physiographic sections of the Colorado Plateaus (modified from Fenneman, 1946).

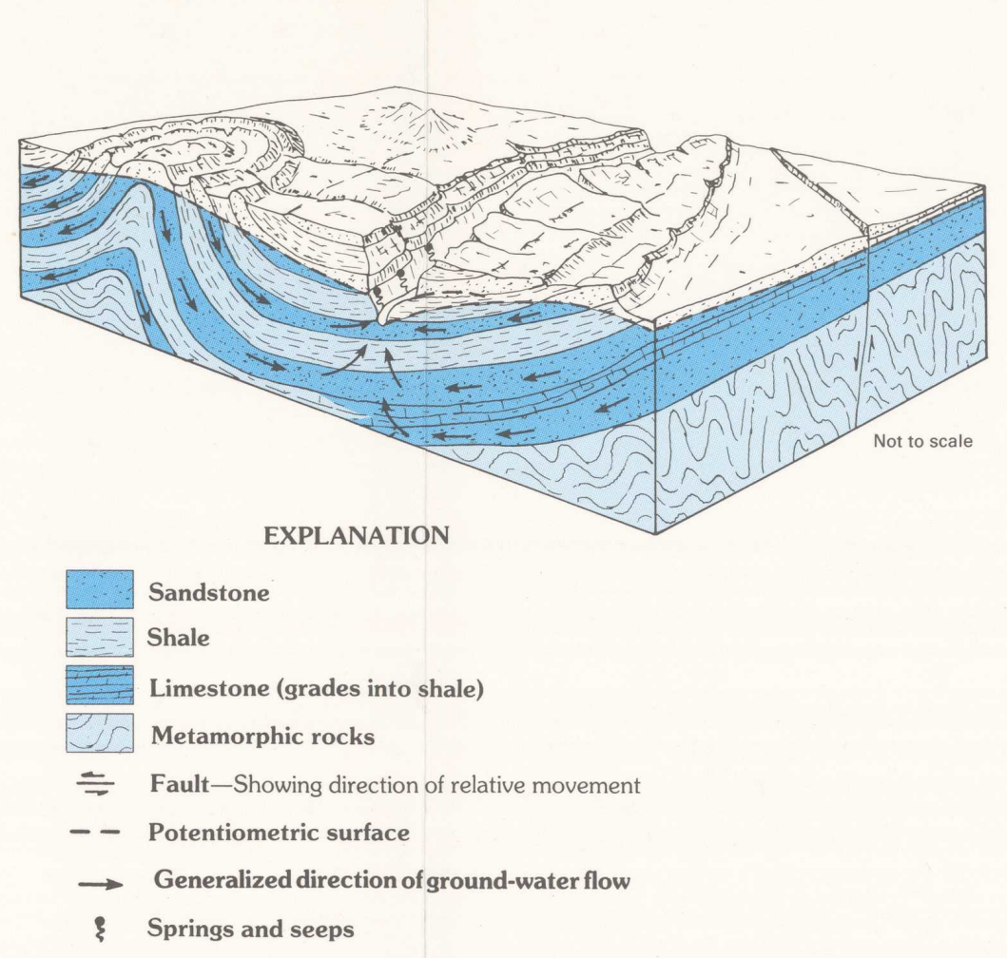

Figure 3.—Generalized physiography and ground-water flow in the Colorado Plateaus (modified from Heath, 1984).

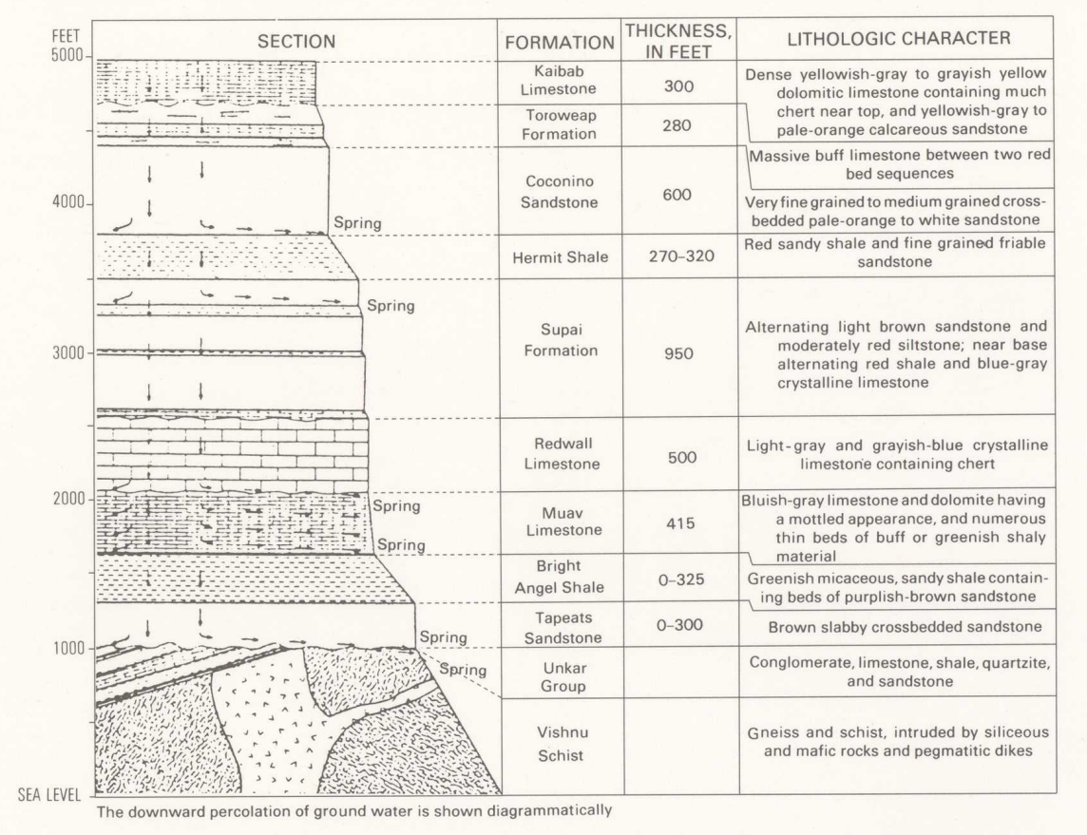

Figure 4.—Geologic section at the Grand Canyon showing stratigraphic controls on ground-water flow (after Metzger, 1961, pl. 14).

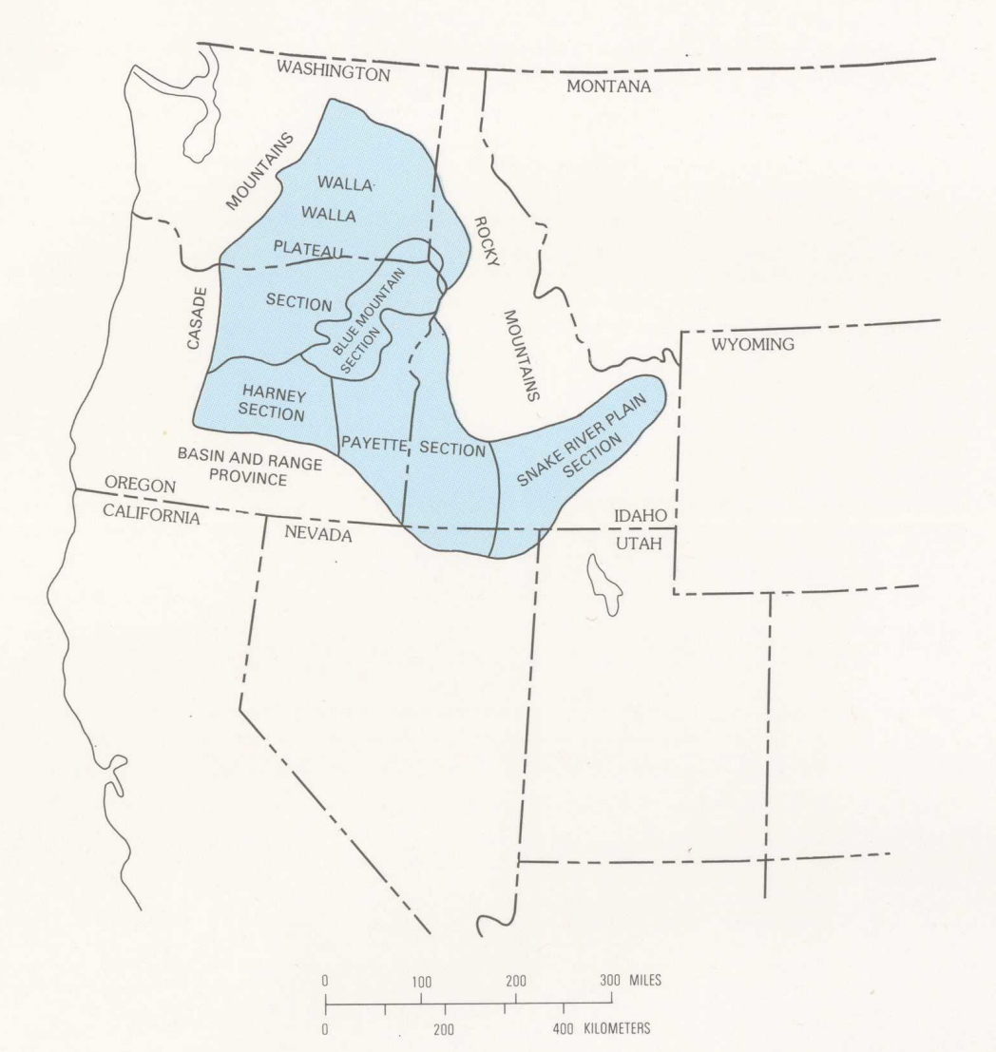

Figure 5.—Physiographic sections of the Columbia Plateaus province (modified from Fenneman, 1946).

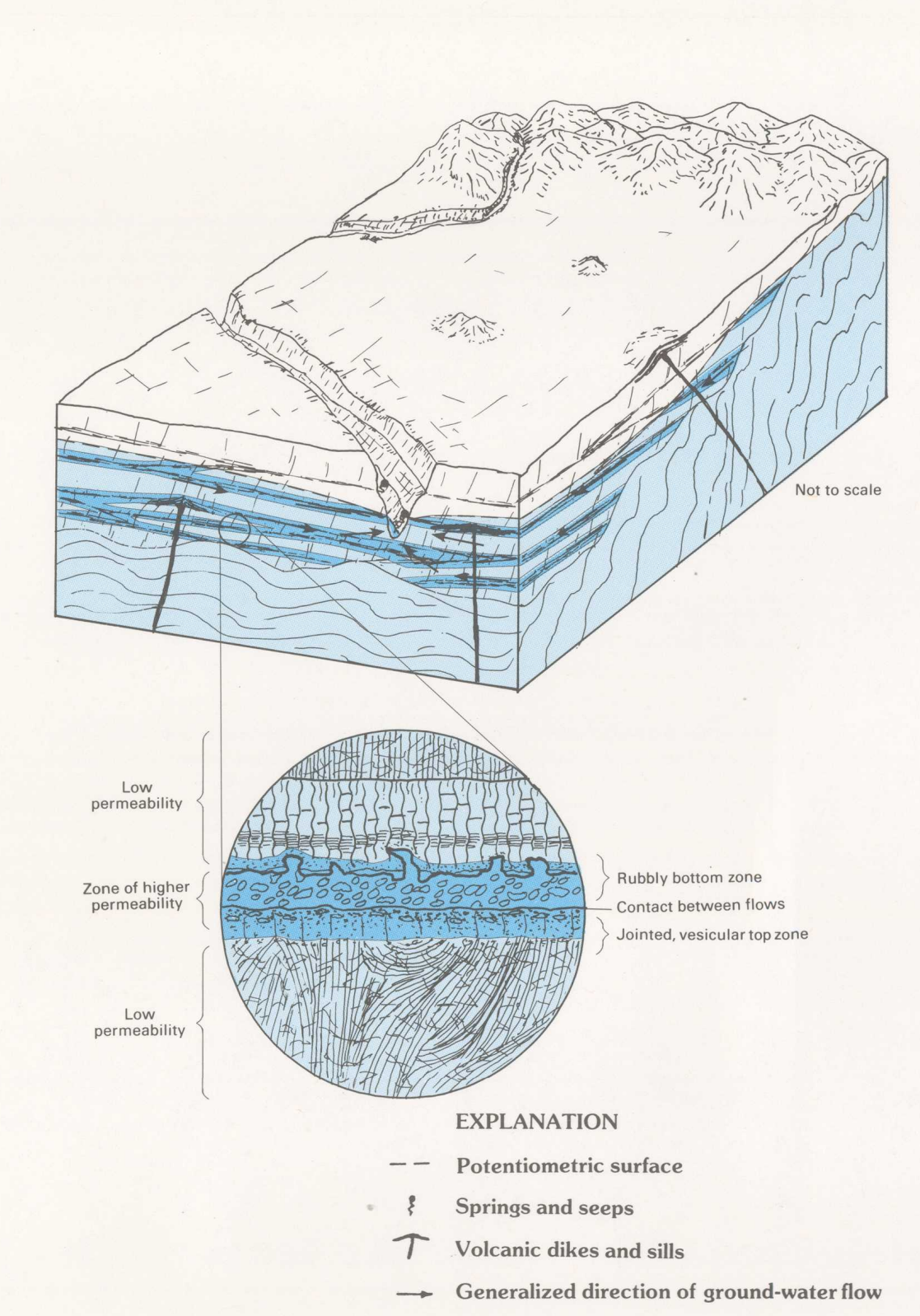

Figure 6.—Generalized physiography, and ground-water flow systems in the Columbia Plateaus (modified from Heath, 1984).

Figure 7.—Physiographic sections of the Pacific Mountain System (modified from Fenneman, 1946).

CONVERSION FACTORS

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.40 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile | 1.609 | kilometer |

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum 1929.

INTERIOR—GEOLOGICAL SURVEY, RESTON, VIRGINIA—1989

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